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CREEP AND FATIGUE RESEARCH EFFORTS ON ADVANCED MATERIALS

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SUMMARY

Two of the more important materials problems encountered in turbine blades of aircraft engines are creep and fatigue. To withstand these high-temperature phenomena modern engines utilize single-crystal, nickel-base superalloys as the material of choice in critical applications. This paper will present recent research activities at Lewis on single-crystal blading material related to creep and fatigue. The goal of these research efforts is to improve the understanding of microstructure-property relationships and thereby guide material development.

Although single crystals exhibit creep properties which are superior to conventionally cast, polycrystalline blading material, recent work at Lewis and other aerospace laboratories has shown that greater improvements can be attained by developing single-crystal alloys with a "rafted" microstructure. In this microstructure, the small, cuboidal γ' precipitates that strengthen these alloys are converted into nearly continuous layers or "rafts" of γ'. The factors, both internal and external, which affect raft formation have been studied from an experimental and analytical standpoint. These include the effect of stress, temperature, lattice misfit, and elastic constants of the precipitate and matrix.

In addition to creep damage, thermomechanical fatigue (TMF) of single-crystal blading material has received much attention in recent years because it is often found to be life limiting. TMF damage results from simultaneous fluctuations of temperature and mechanical loads. Recent work at Lewis on coated single crystals has identified an environmentally driven damage mechanism for the deleterious out-of-phase TMF cycle. Experimental evidence for this mechanism is presented, together with a qualitative model describing the damage mechanism.

INTRODUCTION

The harsh operating environment encountered in the turbine section of an aircraft engine gives rise to numerous materials problems. Two of the more important problems are associated with creep and fatigue damage of turbine blades. Sustained, centrifugal loads on the blades at elevated temperature give rise to creep damage, a time-dependent, permanent elongation. Cyclic loads associated with starting and stopping of the engine, coupled with the simultaneous changes in material temperature, produce thermomechanical fatigue (TMF) damage. Unlike creep damage, TMF damage and subsequent growth of TMF cracks are directly dependent on the number of stress cycles the blades encounter, not on the total exposure time at elevated temperatures.

To withstand the high-temperature loads developed in turbine blades, nickel-base superalloys are used in modern-day engines. These blade alloys can be made as conventional castings or as directionally solidified castings. In the former instance, a random polycrystalline microstructure is produced, whereas, in the latter instance, an aligned polycrystalline microstructure is produced. The directionally solidified casting can also be produced such that the entire blade is a single grain or crystal. In all three forms, the superalloy derives much of its high-temperature strength from the γ' particles. Carbides are also present in the polycrystalline forms to enhance the creep strength of the grain boundaries.

Of the three forms of nickel-base superalloy blading materials mentioned, the single crystal form has the highest temperature, longest life capability because the detrimental effect of grain boundaries is eliminated. Further enhancement of single-crystal fatigue properties is attained by removal of carbides, which improve creep properties of grain boundaries, but also serve as initiation sites for fatigue cracks.

In the following pages I will discuss various aspects of creep and fatigue behavior of advanced single-crystal superalloys which have been the subject of recent research programs at Lewis Research Center.

CREEP BEHAVIOR OF SINGLE CRYSTALS

The typical heat-treated microstructure of modern single-crystal superalloys contains about 60 percent of the γ' precipitates dispersed in a continuous matrix of γ. The γ' particles are usually present as spheres or cubes after heat treatment, and an example of this microstructure is shown in figure 1. However, under an applied stress at elevated temperatures, these discrete γ' particles link up in certain alloys to form plates, which are commonly called γ' rafts. These γ' rafts have been shown to improve the creep life of single crystals at elevated temperatures.

The γ' rafts have a beneficial effect on creep life if they form rapidly and are relatively perfect (ref. 1). An example of a "perfect" rafted microstructure is shown in figure 2 for a single-crystal alloy containing 13.9 percent molybdenum. However, when the molybdenum content of the alloy was increased slightly to 14.6 percent, an additional phase forms which causes imperfections or gaps in the rafts. An example of this discontinuous rafted structure is also shown in figure 2. The degradation in raft perfection causes a dramatic decrease in the creep life. Thus, our research is aimed at understanding the mechanisms of this phenomenon to exploit the maximum benefit from rafted microstructures.

A major factor which influences γ' rafting behavior is the lattice mismatch. The magnitude of the lattice mismatch indicates the difference in lattice parameters (the dimensions of the atomic structure) between the γ and γ' phases. The sign of the mismatch is one factor which determines the orientation of the rafted structure. Superalloys with large, negative values of lattice mismatch form rafts perpendicular (P-type) to the applied tensile axis, whereas alloys with large, positive values of mismatch form rafts parallel (N-type) to the applied tensile axis. However, the sign of the mismatch can actually change from positive to negative as temperature increases (ref. 2). Thus P-type rafts can form at elevated temperatures in some alloys which have a small positive mismatch at room temperature. It is therefore important to obtain lattice mismatch measurements at elevated temperatures in order to make accurate predictions of raft orientation.

To further our understanding of the rafting process, a field-oriented, microstructural lattice model (fig. 3) was developed (ref. 3). In this approach the microstucture is discretized onto a fine lattice. Each element in the lattice is labeled accordingly as γ or γ'. Diffusion, that is, physical transport of material at elevated temperatures, is simulated by allowing exchanges of neighboring elements if the exchange lowers the total energy of the system. A Monte Carlo approach is used to select the exchange site, whereas the change in energy associated with the stress fields, that is, precipitate misfit and external creep load, is computed by using a finite-element technique.

To date, simulations of the rafting phenomenon in single crystals agree with real-world behavior. The orientation of the rafted structure under tensile loads and its dependence on precipitate misfit is illustrated in figure 4. The two alloys shown have identical properties and starting microstructures, except that one has a negative misfit and the other has a positive misfit. Rafting simulations run on both alloys show that rafts develop which are perpendicular to the stress axis for negative misfit but parallel to the stress axis for positive misfit. This is consistent with the experimental results.

FATIGUE BEHAVIOR OF SINGLE CRYSTALS

Although the creep damage produced at high temperatures by sustained loads affects the life of single-crystal turbine blades, failure is often attributed to thermomechanical fatigue damage. This damage is produced by the application of cyclic loads during heating and cooling of the blade. The damage often starts as cracks in the oxidation-resistant coating applied to single-crystal turbine blades. These cracks grow into the single crystal and eventually cause failure of the blade (fig. 5).

Thermomechanical fatigue (TMF) is particularly harmful in cycles where tensile loads are applied at temperatures below 800 °C, where ductility of superalloys is lowest. A TMF cycle of this type is termed out-of-phase (OP) and is often encountered in real engine cycles. Here the load and temperature change in opposite directions at the same time. This cycle produces tensile mechanical strains at the minimum temperature and compressive mechanical strains at the maximum temperature. Analysis is complicated, since the mechanical strain due to the changing load is mixed with thermal strains due to the changing temperature.

A large body of knowledge exists on fatigue damage produced by cyclic loads at constant temperature. This understanding cannot be easily applied to the TMF problem, where cyclic loads produce damage at continuously changing temperatures. But the "bithermal" TMF cycle provides the means to apply this knowledge. In this simplified TMF cycle, equal amounts of inelastic mechanical strain, of opposite sign, are applied at the temperature extremes in the cycle.

The inelastic strain is a permanent, or nonrecoverable, strain which produces damage within the material (fig. 6).

The bithermal TMF cycle produces the same type of damage as the more realistic TMF cycle (ref. 4). In out-of-phase (OP) tests where the temperature is changed between 650 and 1050 °C, both cycles produce premature surface cracks. Surface cracking also occurs in constant-temperature fatigue tests at 650 °C, and, at high cyclic strains, all cycles have comparable life. But in tests at low cyclic strains, the OP TMF life is up to 10 times shorter than in tests at 650 °C, as shown in figure 7.

At low strains, foreshortening of cyclic life in the OP bithermal TMF test results in part from oxidation damage at 1050 °C. When these tests are performed in vacuum (fig. 8), the OP bithermal TMF test lives increase and are approximately equivalent to the constant-temperature tests at 650 °C. Early surface cracking occurs in all of these tests, the OP bithermal TMF tests and the constant-temperature tests at 650 °C in both air and vacuum. Therefore oxidation at 1050 °C apparently accelerates growth of surface cracks in the OP bithermal TMF test.

In figure 9 a simple model of the damage mechanism for the OP bithermal cycle is presented which explains life degradation at low strains. It is assumed that surface cracks appear early in all tests. The crack tips are oxidized and thereby embrittled at 1050 °C. In tests employing large cyclic strains, the crack grows far beyond the embrittled region during a single cycle. Therefore the crack growth resistance of the unoxidized superalloy controls life, and oxidation at 1050 °C has little effect. But in tests at small cyclic strains, crack growth in the superalloy is slow compared to the advance of the oxidized region. Fracture of this environmentally damaged zone requires little load at low temperatures, such as 650 °C, and therefore provides a faster crack growth rate and shorter life at lower cyclic strains.

CONCLUSIONS

In this paper various aspects of recent research programs, on advanced single-crystal superalloys, at Lewis Research Center have been discussed. The first part of this paper discussed creep behavior and the beneficial effects of the rafted microstructure in single crystals. In the second part of this paper, the thermomechanical fatigue behavior of coated single crystals was discussed with particular attention given to the deleterious effect of the environment. Both experimental and analytical aspects of these activities were highlighted.

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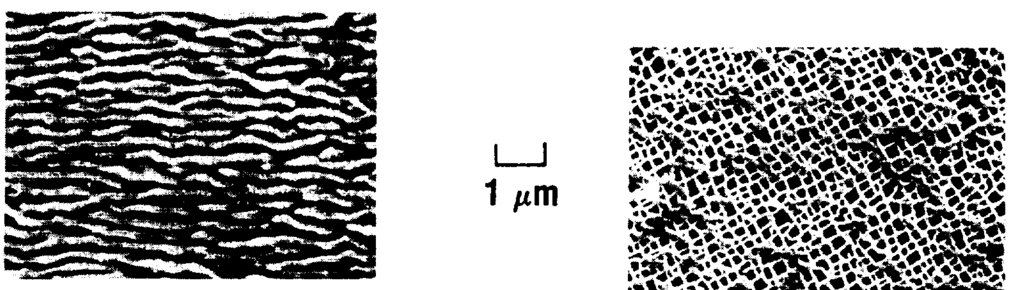

60 % FINE γ′ STRENGTHENING PHASE

RAFTED γ′

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Figure 1. - Starting and rafted microstructure of single-crystal superalloy.

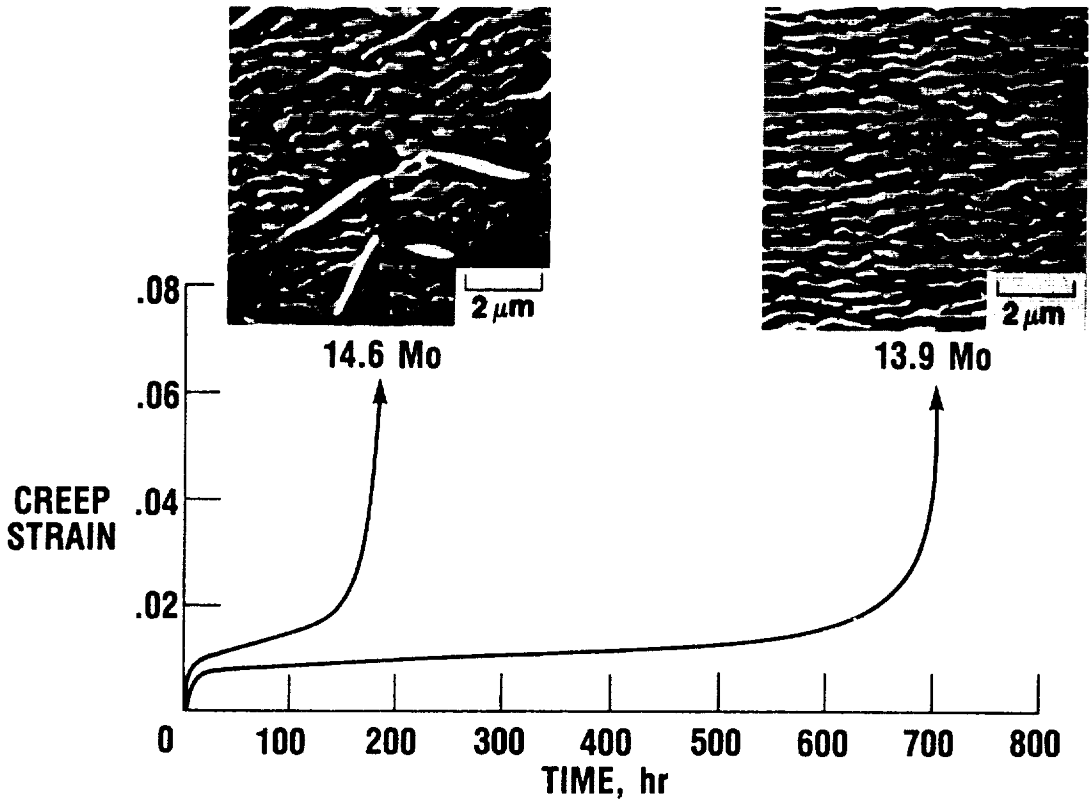

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Figure 2. - Effect of raft perfection on creep life.

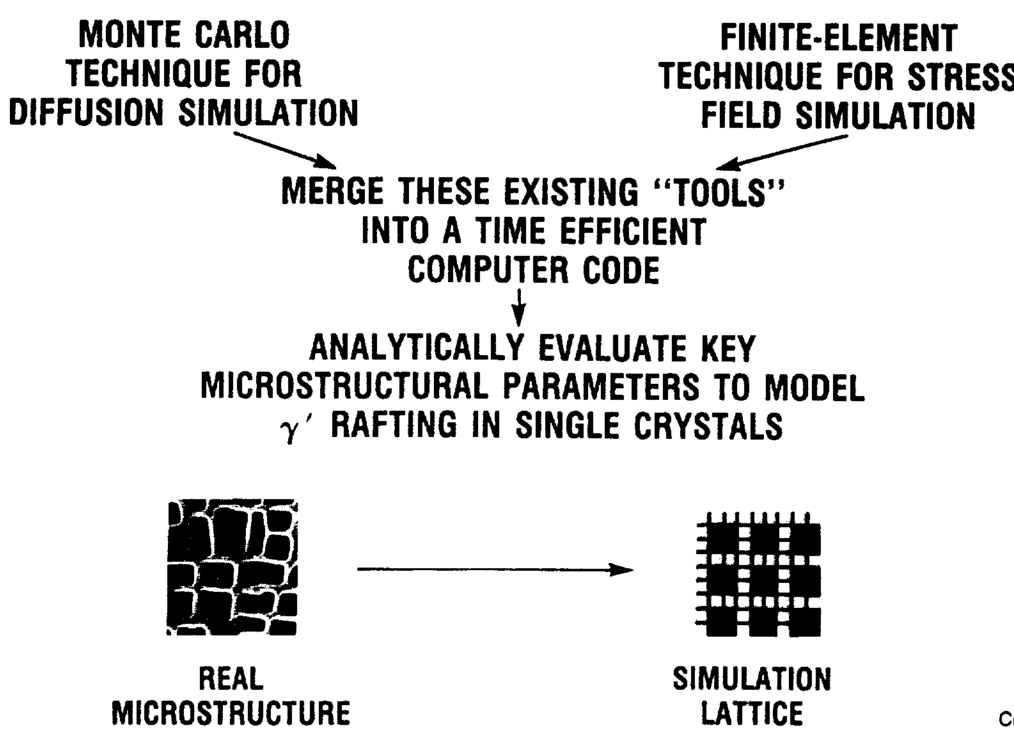

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Figure 3. - Schematic representation of microstructural lattice model used to analyze rafting phenomenon.

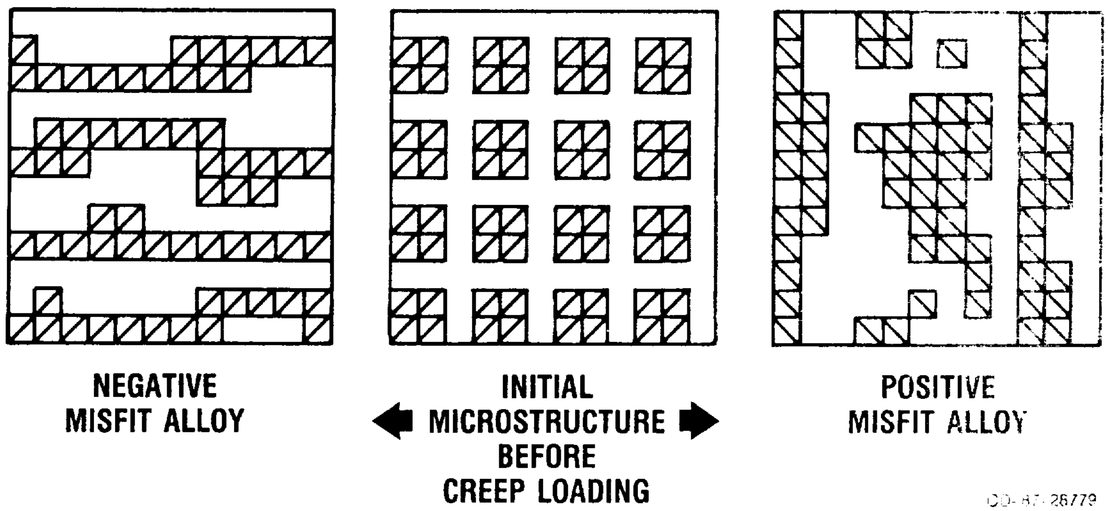

Figure 4. - Simulated rafting of positive and negative misfit alloys

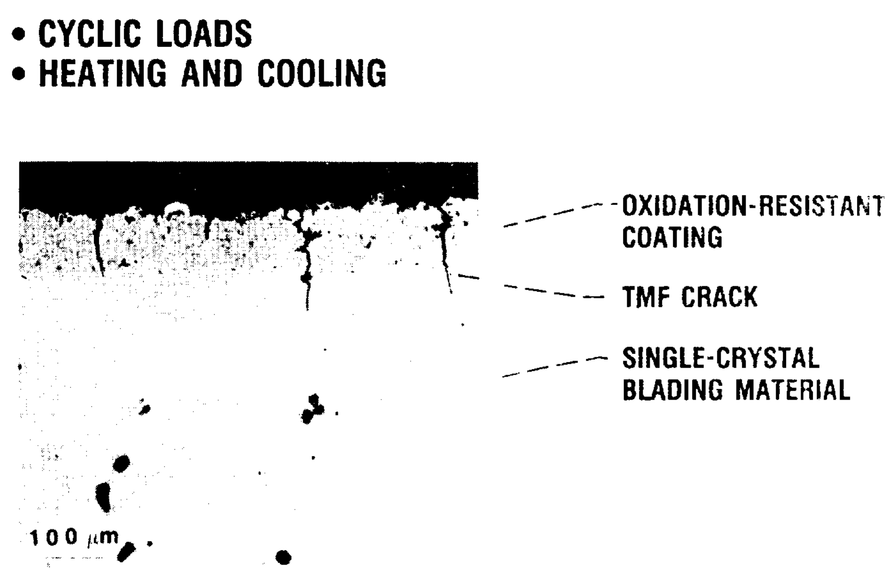

Figure 5. - TMF cracking in coated single-crystal alloy.

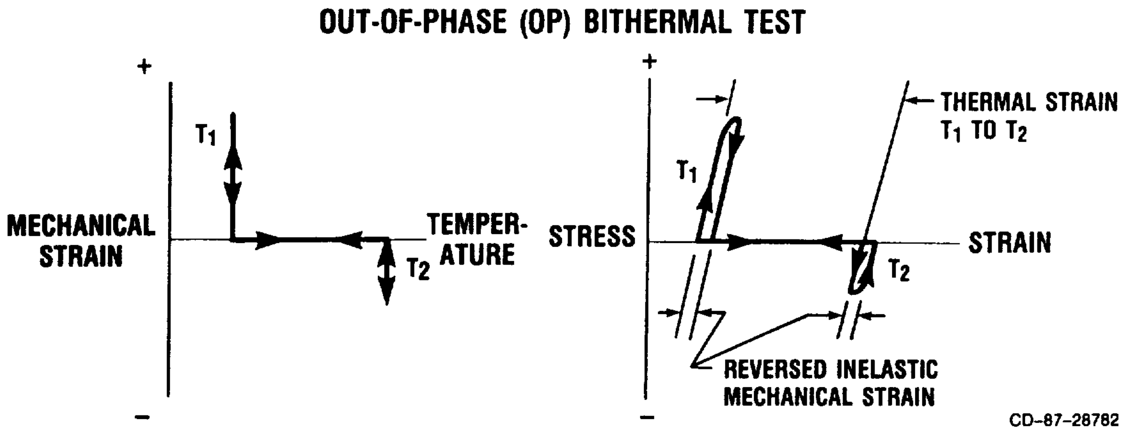

Figure 6. - Definition of bithermal fatigue cycle.

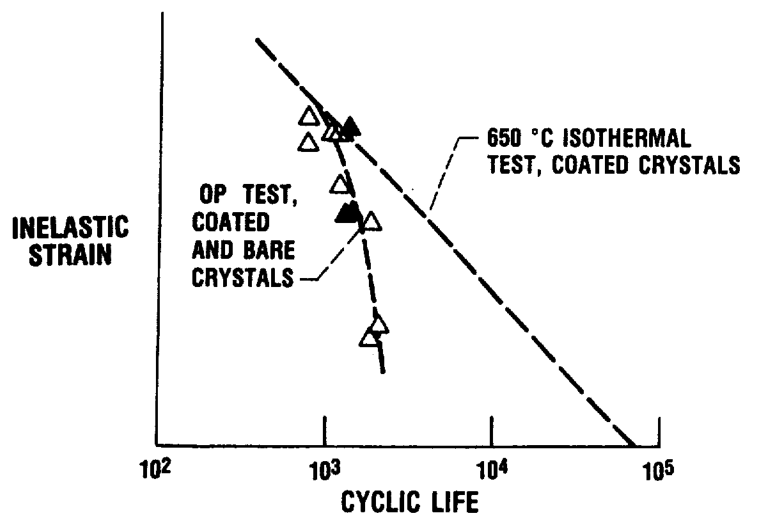

Figure 7. - Comparison of out-of-phase bithermal and 650 °C isothermal fatigue lives.

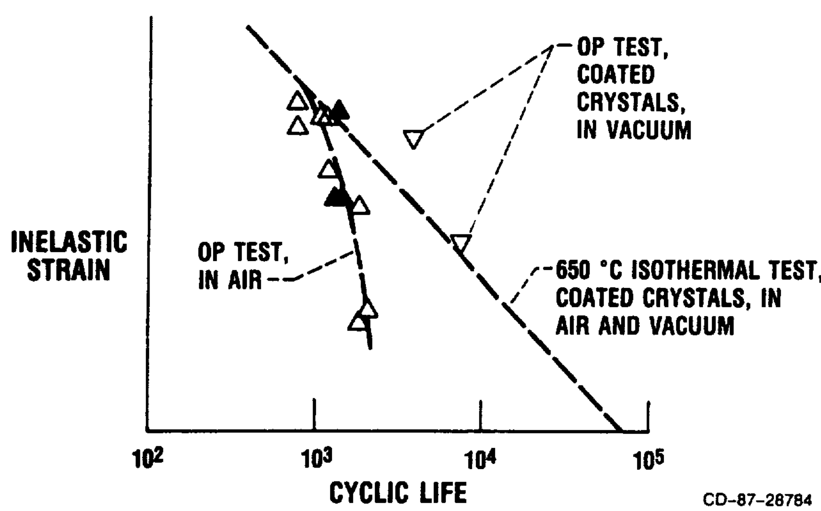

Figure 8. - Short life of bithermal out-of-phase tests largely associated with environmental effects.

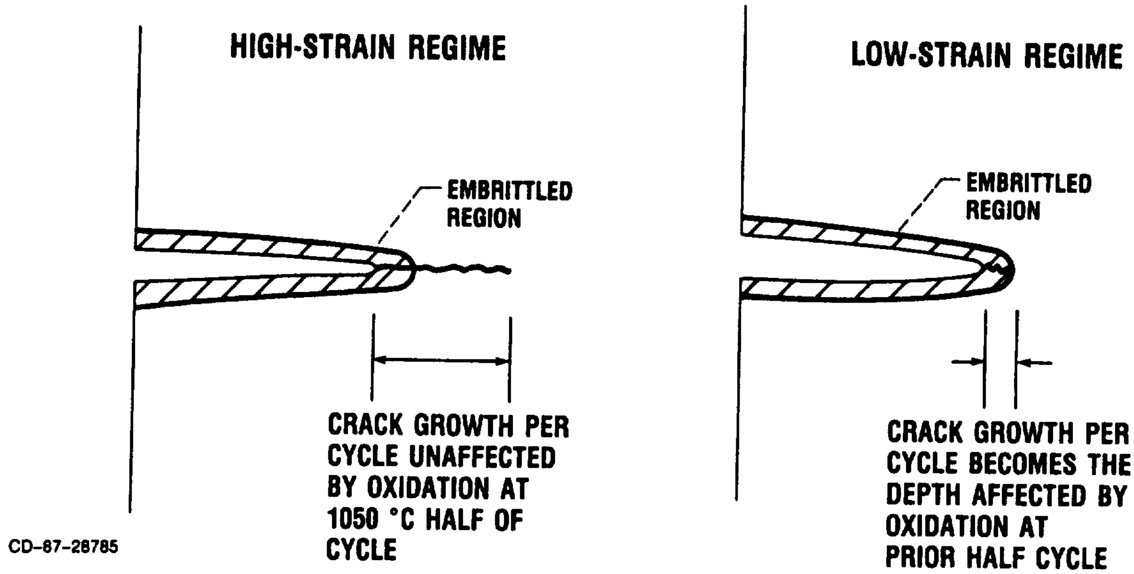

Figure 9. - Schematic representation of environmentally assisted crack growth mechanism for out-of-phase TMF tests.